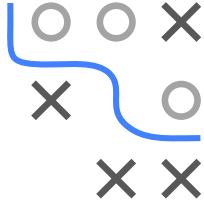
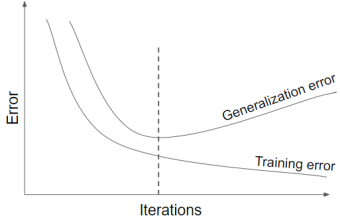
Introduction to Machine Learning



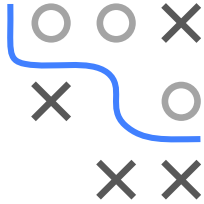
Early Stopping



Learning goals

- Know how early stopping works
- Understand how early stopping acts as a regularizer
- Know early stopping imitates *L2* regularization in some cases

EARLY STOPPING



- When training with an iterative optimizer such as SGD, it is commonly the case that, after a certain number of iterations, generalization error begins to increase even though training error continues to decrease.
- **Early stopping** refers to stopping the algorithm early before the generalization error increases.

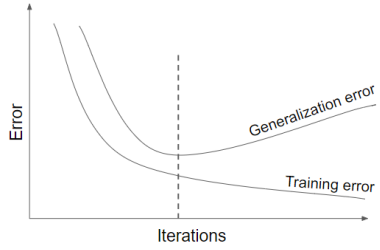


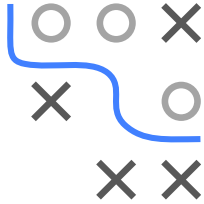
Figure: After a certain number of iterations, the algorithm begins to overfit.

EARLY STOPPING

How early stopping works:

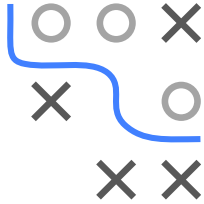
1. Split training data $\mathcal{D}_{\text{train}}$ into $\mathcal{D}_{\text{subtrain}}$ and $\mathcal{D}_{\text{val}}$ (e.g. with a ratio of 2:1).
2. Train on $\mathcal{D}_{\text{subtrain}}$ and evaluate model using the validation set $\mathcal{D}_{\text{val}}$.
3. Stop training when validation error stops decreasing (after a range of “patience” steps).
4. Use parameters of the previous step for the actual model.

More sophisticated forms also apply cross-validation.



EARLY STOPPING AND *L2* ▸ GOODFELLOW ET AL., 2016, P. 249 FF.

Strengths	Weaknesses
Effective and simple	Periodical evaluation of validation error
Applicable to almost any model without adjustment	Temporary copy of $\boldsymbol{\theta}$ (we have to save the whole model each time validation error improves)
Combinable with other regularization methods	Less data for training $\rightarrow$ include $\mathcal{D}_{\text{val}}$ afterwards



- For simple case of LM with squared loss and GD optim initialized at $\boldsymbol{\theta} = 0$: Early stopping has exact correspondence with *L2* regularization/WD: optimal early-stopping iter T_{stop} inversely proportional to λ scaled by step-size α

$$T_{\text{stop}} \approx \frac{1}{\alpha\lambda} \Leftrightarrow \lambda \approx \frac{1}{T_{\text{stop}}\alpha}$$

- Small λ (regu. $\downarrow$) $\Rightarrow$ large T_{stop} (complexity $\uparrow$) and vice versa

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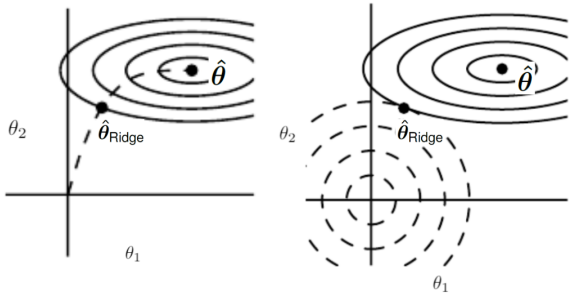


Goodfellow et al. (2016)

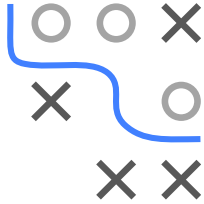
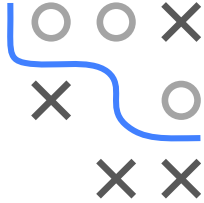
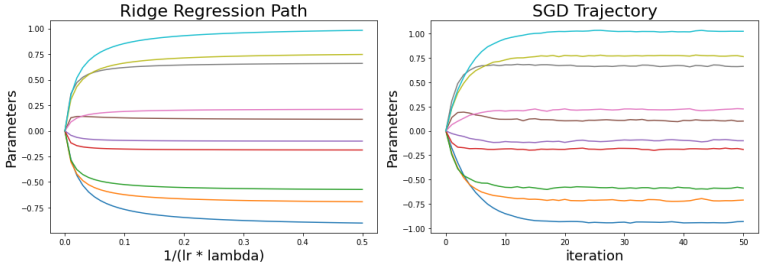


Figure: Effect of early stopping. *Left:* The solid lines indicate contours of the square loss objective. Dashed line indicates trajectory taken by GD initialized at origin. Instead of reaching minimizer $\hat{\theta}$, ES results in trajectory stopping earlier at $\hat{\boldsymbol{\theta}}_{\text{ridge}}$. *Right:* Effect of *L2* regularization. Dashed circles indicate contours of *L2* constraint which push minimizer of regularized cost closer to origin than minimizer of unregularized cost.

SGD TRAJECTORY AND *L2* ▸ ALI ET AL., 2020

Solution paths for *L2* regularized linear model closely matches SGD trajectory of unregularized LM initialized at $\theta = 0$





Caveat: Initialization at the origin is crucial for this equivalence to hold, which is almost never used in practice in ML/DL applications